

Comparison of split post dielectric resonator and ferrite disc resonator techniques for microwave permittivity measurements of polycrystalline yttrium iron garnet

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Abstract. Two techniques are evaluated for the accurate measurement of the microwave permittivity of polycrystalline yttrium iron garnet (YIG) at frequencies between 5.5 and 12.5 GHz: split post dielectric resonator (SPDR) and ferrite disc resonator (Courtney). Both techniques separate YIG permittivity from that of YIG permeability by applying a magnetic induction bias to the YIG sample under test. The SPDR method needs no special sample preparation in the case of YIG substrates, whereas the Courtney method requires the grinding of rods from bulk YIG. The Courtney measurements of the YIG real permittivity are found to be higher on average than SPDR measurements. Agreement between the two techniques improves with increasing magnetic induction bias.

Keywords: complex permittivity, dielectric losses, dielectric property measurements, split post dielectric resonator technique, yttrium iron garnet permittivity

1. Introduction

Several techniques to measure the complex permittivity of low-loss ferrite materials at microwave frequencies have been described. Resonance methods are considered preferable because they offer the highest accuracy in the measurement of dielectric loss [1–4]. There are two ways to separate the measurement of the dielectric properties of ferrite (permittivity) from the magnetic properties (permeability). One approach is to measure a demagnetized ferrite sample at two different positions in the fixture(s) (resonators or transmission line) that map to different electromagnetic field distributions. These positions correspond typically to the maximum and to the minimum of the electric field in the sample [4]. The other approach is to apply a very strong static magnetic induction during the microwave measurement so that the relative permeability tensor of the ferrite material under test becomes sufficiently close to the identity tensor, which makes it possible to treat the material as a dielectric [3].

Both techniques have advantages and disadvantages. One important disadvantage of the first technique is that the permeability of a demagnetized ferrite material is never a

true scalar quantity because the magnetic domain distribution (which determines permeability) depends on the shape of the ferrite sample. For example, thin ferrite substrates have one dimension much smaller than the other two, which results in an anisotropic magnetic domain distribution. Furthermore, the microwave magnetic field distribution changes from one point to another in measurement fixtures in the first technique. That means that the direction of the magnetic field is usually different at two different sample positions inside the fixture where the sample is placed to determine both permittivity and permeability. If the permeability is not scalar as discussed above, then the assumption that it is identical in these two positions is not valid, hence compromising the accuracy of the first technique.

In the second technique, it is assumed that for a sufficiently strong biasing field the permeability of the ferrite material under test becomes equal to unity. This is true in typical experiments for the permeability tensor component parallel to the biasing field, but not necessarily for the tensor components perpendicular to that field [4]. If the microwave magnetic field in the measurement fixture has a significant tensor component perpendicular to the biasing field then the

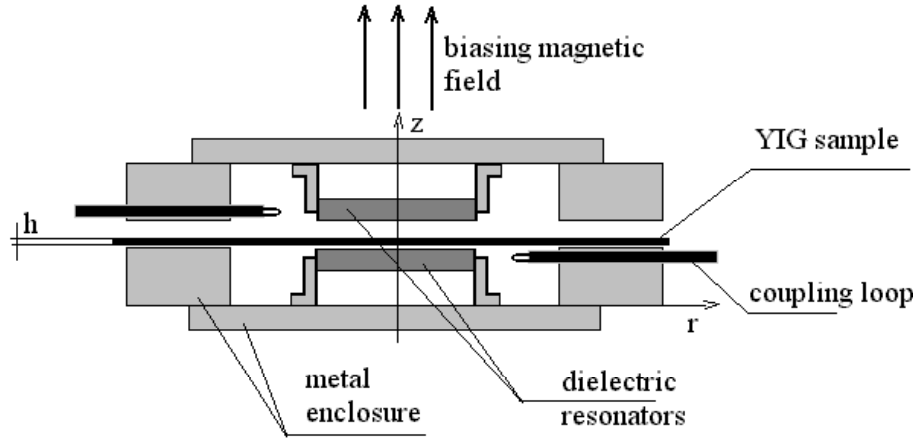


Figure 1. Sketch of side view of a split post dielectric resonator. For a 5.5 GHz resonator, the cavity diameter and length were 24.0 and 12.8 mm respectively.

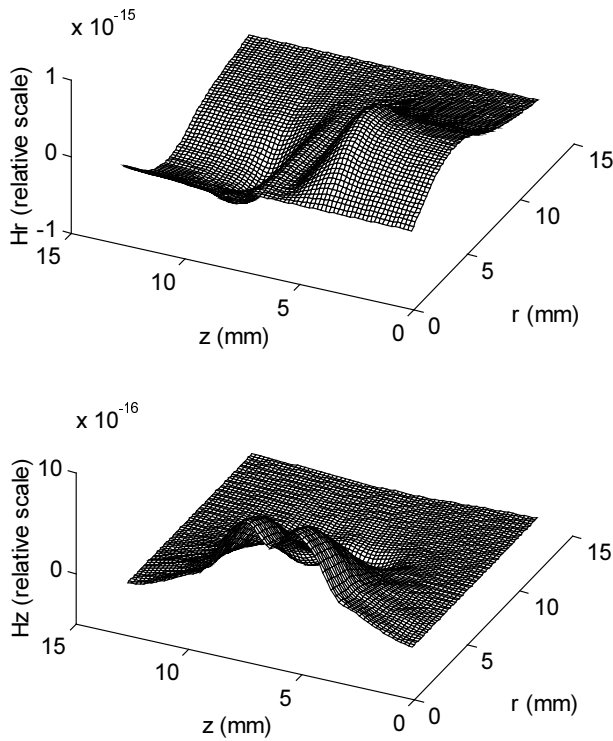


Figure 2. Magnetic field distribution in a 5.5 GHz split post dielectric resonator.

permeability tensor cannot be treated as identity tensor—even for a very strong magnetic bias induction.

In this paper we compare two variations on the second technique for the accurate measurement of the complex microwave permittivity for a very soft magnetic material: (1) a split post dielectric resonator (SPDR); and (2) a ferrite disc resonator (Courtney). The magnetic material chosen to evaluate the SPDR and Courtney techniques is polycrystalline yttrium iron garnet (YIG). Both techniques separate the YIG permittivity from that of YIG permeability by applying a magnetic induction bias to the YIG sample under test. The following sections provide a theoretical background to the SPDR and Courtney techniques, the results of our experiments and conclusions.

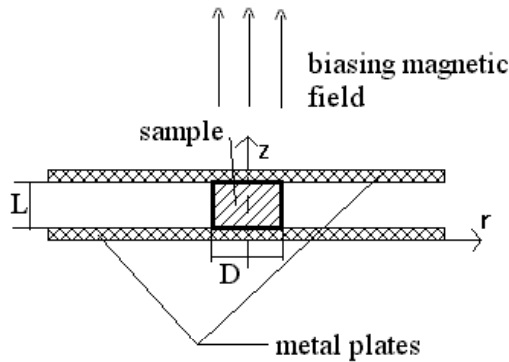
2. Measurement techniques

The SPDR technique has been used for measurements of dielectric materials in general, but especially for dielectric substrates [5–7]. A description of the method can be found in [7]. A sketch of a SPDR is shown in figure 1. The quasi TE_{011} mode is typically dominant for split post resonators loaded with relatively thin samples; however for thick samples the hybrid quasi HE_{111} mode would be the first appearing on the frequency axis. We applied a static magnetic induction perpendicular to the substrate to separate permittivity from permeability for the YIG material. For a sufficiently strong static magnetic induction, the permeability tensor component parallel to the biasing field (perpendicular to the substrate) approaches unity. The microwave electric and magnetic fields are as follows for the YIG substrate inserted in the SPDR fixture: (1) the magnetic field (H_z) components perpendicular to the face of the substrate are significant; (2) the electric field component parallel to the face is significant, but the magnetic field (H_r) component parallel to the face of the substrate approaches a null value. The magnetic field distribution in a 5.5 GHz SPDR is shown in figure 2. This microwave magnetic field distribution means that the permeability tensor components parallel to the face of the substrate have very little effect on the resonant frequency of the quasi TE_{011} mode. This decoupling of microwave electric and magnetic fields makes it possible to measure the permittivity parallel to the face of the YIG substrate accurately. Only when these permeability tensor components are very large can one notice their influence on the effective permittivity parallel to the face. For example, this occurs when static magnetic biasing induction is applied; this corresponds to ferromagnetic resonance for the magnetic material under test.

The ferrite disc resonator technique (Courtney) is depicted in figure 3, and its mode of operation is also TE_{011} . In this case, the microwave magnetic field component perpendicular to the static magnetic biasing induction is substantial, especially for samples of large aspect ratio. Thus, the variation in effective permittivity versus static magnetic biasing field is larger for the Courtney method than for the SPDR method, which has virtually no microwave magnetic

Table 1. Computed mode spectra f_c for YIG rod samples with $k = 15.6$ and $\mu = 1$.

$D = 15.00$ mm, $L = 5.00$ mm		$D = 15.00$ mm, $L = 10.00$ mm		$D = 5.00$ mm, $L = 10.00$ mm	
Mode	f_c (GHz)	Mode	f_c (GHz)	Mode	f_c (GHz)
HE ₁₁₁	8.392	HE ₁₁₁	5.143	HE ₁₁₁	10.681
TE ₀₁₁	9.186	TE ₀₁₁	6.030	TE ₀₁₁	12.625
HE ₂₁₁	9.556	HE ₂₁₁	6.909	TM ₀₁₁	14.285

**Figure 3.** Sketch of side view of ferrite disc resonator (or Courtney resonator).

field component perpendicular to the static magnetic biasing induction.

If samples of unknown materials are measured by the Courtney technique, the TE₀₁₁ mode can be identified properly from the spectrum of spurious modes. The mode spectrum density typically increases for samples of large aspect ratio. Table 1 presents results of computations of the TE₀₁₁ mode and two neighbouring modes' resonant frequencies for three samples having the same dimensions as the samples used in our experiments described in the following section. The computations in table 1 assume a real permittivity (k) of 15.6 and real permeability (μ) of 1 for the YIG specimen under test. In principle, the TE₀₁₁ mode is the second versus frequency for 'infinite' static magnetic induction bias. In practice, hybrid modes (all HE and EH modes are hybrid) typically appear as doublets (with frequency split decreasing versus bias) so in practice two resonances appear below the TE₀₁₁ mode.

3. Experiments

Microwave complex permittivity measurements with SPDR fixtures under static magnetic field bias presented some challenges. First and foremost, it was necessary to determine if static magnetic induction affected the SPDR test fixture itself. A static magnetic induction will exert a magneto-mechanical force on the YIG test specimen, and the test fixture itself, if it contains any magnetic parts, such as steel screws. These magneto-mechanical forces can potentially distort the test fixture and thereby change the resonator spacing. An unknown change in resonator spacing during the experiment would affect the value of the effective permittivity.

Various test fixture modifications and experiments were performed until the magneto-mechanical effect was not detectable. First, the unloaded resonance was measured

Table 2. Effective permittivity of YIG and real permittivity of silicon measured by the SPDR method. Thickness of the samples: YIG, 503 ± 0.13 μm ; silicon, 383 ± 0.13 μm .

f (GHz)	B (T)	ϵ_{eff} (YIG)	ϵ (silicon)	Test operator
5.5	0.7332	15.44	11.71	1
5.5	0.7950	15.45	11.67	2
6.8	0.8275	15.49	11.66	1
6.8	0.8181	15.47	11.66	2
8	0.7996	15.42	11.58	1
8	0.8389	15.45	11.61	2

Table 3. Real permittivity of silicon measured by the Courtney method.

f (GHz)	ϵ (silicon)	Test operator
5.84	11.673	1
6.94	11.674	1
9.29	11.681	1
5.84	11.675	2
9.29	11.683	2
9.29	11.677	2

without and with static magnetic biasing induction equal approximately to 0.8 T (the maximum applied magnetic induction for SPDR technique). Second, the first experiment was repeated but with the SPDR test fixture loaded with YIG material surrounding (but not penetrating) the interrogation region in order to test the interaction between the test sample and test fixture. Finally, a wafer of single crystal, high-resistivity silicon was measured without bias, and at 0.8 T. Single crystal silicon was selected since it is a homogeneous, isotropic, pure dielectric (non-magnetic) material, with dielectric constant reasonably close to that of YIG.

In our experiments, we used three SPDR test fixtures designed to operate at microwave frequencies of 5.5, 6.8 and 8 GHz respectively. The material properties of the dielectric resonators used in the construction of SPDR fixtures were permittivity about 30 (the exact value was calculated from resonant frequency of empty fixtures) and dielectric loss tangent 7×10^{-5} at 10 GHz. The results of measurements of the effective permittivity of various samples using the SPDR and Courtney techniques are presented in figure 4 and in tables 2 to 5. In figure 4, ferromagnetic resonances are clearly visible for the SPDR technique at biasing fields 0.4–0.5 T (resonance field is frequency dependent). These resonances correspond to the singularities in the measured effective permittivity plotted as a function of applied magnetic bias in figure 4. At small biasing fields below ferromagnetic resonance, the effective permittivity changes because of variations in the permeability tensor component parallel to the biasing field. Figure 4 also shows that when the static biasing magnetic induction is larger than 0.7 T the effective permittivities measured at all frequencies converge to a single

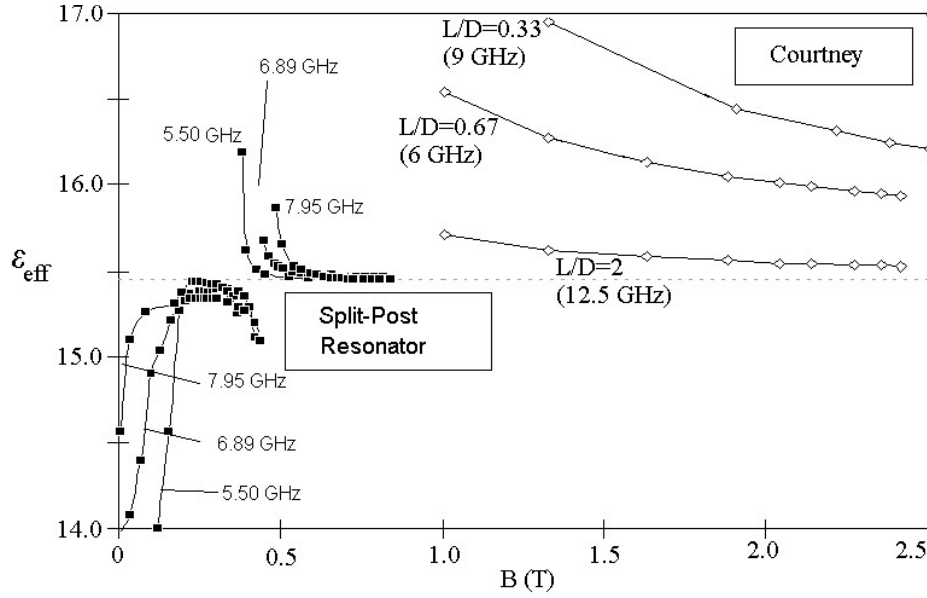


Figure 4. Effective permittivity of YIG versus biasing magnetic induction measured by the SPDR and Courtney techniques.

value, which implies that the permeability tensor component parallel to the biasing induction is effectively equal to one for the three frequencies (5.50 GHz, 6.89 GHz and 7.95 GHz) covered by the three SPDR test fixtures.

Measurement results of the effective microwave permittivity of YIG and real permittivity of high-resistivity silicon by means of the SPDR method are shown in table 2. Measurements were performed independently by two test operators. The static magnetic induction bias indicated in table 2 was applied only to the YIG samples. Effective permittivities of YIG measured at different fixtures and by different operators varied no more than 0.26% with respect to their average value. Slightly larger variations in measured permittivity values were observed for the silicon sample.

Tables 3 to 5 show the results of experiments using the Courtney technique. For silicon, the microwave real permittivity values measured by Courtney and SPDR methods agree to within 0.26%. The effective permittivity for YIG obtained by the Courtney method is larger than the values obtained by the SPDR method in spite of the very large static magnetic bias. This difference increases with decreasing aspect ratio (L/D = length/diameter) of the disc samples (see figure 4). The best agreement between the SPDR and Courtney microwave real permittivity (to within 0.52%) was for the Courtney measurement on the YIG sample with the largest L/D ratio of 2 (see figure 4, and compare results in tables 2 and 4). The SPDR technique is more convenient than the Courtney method for microwave permittivity measurements of magnetic or dielectric substrates, but the Courtney method does have higher resolution than the SPDR technique for dielectric loss measurements. This is because the electric energy filling factor for the Courtney method is about five to ten times larger than for the SPDR. The dielectric loss resolution for the Courtney method is of the order of 1×10^{-5} , while that for the SPDR method is about 5×10^{-5} (for a sample thickness of about 0.5 mm) to 1×10^{-4} , (for a sample thickness of about 0.25 mm).

Table 4. Effective permittivity of YIG measured by the Courtney method. $L/D = 2$.

f (GHz)	B (T)	ϵ_{eff}	Test operator
12.5	2.4203	15.527	1
12.5	2.3792	15.531	2

Table 5. Effective permittivity and dielectric loss tangent of YIG samples from different companies measured by means of the Courtney method. $L/D = 0.67$, $f = 6$ GHz, $B = 2$ T.

Vendor	ϵ_{eff}	$\tan \delta$
1	15.872	0.00016
1	15.875	0.00017
2	16.048	0.00005
2	16.032	0.00005
3	16.108	0.00007
3	16.160	0.00007

YIG is very low-loss material and its dielectric loss can be accurately measured using only the Courtney technique. Results of dielectric loss measurements of YIG samples from different vendors are shown in table 5. Unfortunately, the aspect ratios of these samples were too small for precise measurements of their real permittivity in our electromagnet, but their dielectric losses were accurately measured.

4. Conclusions

The split post dielectric resonator (SPDR) technique has been shown to be very effective and accurate for measurements of the microwave real permittivity of YIG substrates. The SPDR method needs no special substrate preparation, whereas the Courtney method requires the grinding of relatively large rods. In the SPDR method, a static magnetic biasing induction of the order of 0.8 T is sufficient to measure the microwave real permittivity of a YIG substrate, which can be considered to be the real permittivity of YIG. Courtney

measurements of permittivity are found to be higher on average than SPDR measurements due to the influence of permeability which cannot be completely eliminated even for large biasing fields ($B > 2$ T). Agreement between the two techniques improves with increasing magnetic induction and with increasing aspect ratio (L/D). The Courtney method is more accurate than the SPDR method for dielectric loss measurements of YIG.

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